Space Interferornetry Mission:
New System Engineering Approaches, Tools, Models and Testbeds

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Abstract -- in 2005, NASA's Origins Program will launch the Space Interferometry Mission (SIM), a 10 meter optical interferometer instrument, into a circular 900 km earth orbit. This instrument will be comprised of three collinear optical interferometers whose prime mission objectives are to perform astrometric measurements of unparalleled accuracy and to perform rotational synthesis imaging of stellar debris disks.

To deal with the huge technical challenges of developing this instrument, innovative approaches to System Engineering are being tested and applied in order to achieve our target performance objectives. Defining requirements flow down from the highest system level to the detailed equipment specifications demands a tracing capability that has not been previously available or maintainable on past projects. The SIM System Engineering activity has chosen to utilize a requirements tracing tool to help it track changes and, hopefully, limit volumes of documentation that have become burdens in the past. Additionally, cross-cutting system models will be applied using new processes and infrastructure being instituted at JPL.

Detailed models of optical systems, structural dynamics and thermal control systems are being implemented in an integrated fashion. The fidelity of these models will be verified in a series of evolving hardware and software testbeds that will culminate in a functioning ground version of the flight system. This testbed, supported by a separate technology program, will validate the system level requirements on astrometric performance, visibility and throughput. SIM will be one of the first missions to apply all of these techniques to enhance design detail and mitigate or retire risk early in it's development cycle.

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1. Introduction

The Space Interferometry Mission (SIM) is a cornerstone mission in NASA's Origins Program. To be launched aboard a Delta II - 7920 launch vehicle in 2005, SIM will be placed in a "dawn-dusk" orbit of 900 km with an inclination of99 degrees. After an initial period of on-orbit calibration and check-out, the instrument will begin a five year mission to obtain detailed and highly accurate astrometric measurements of stellar objects and images of stellar debris disks. This mission will make measurements with far greater accuracy than is possible from Ground-based observations. A mission wide angle astrometric accuracy of 4 microarcseconds is required.

The SIM design uses three collinear interferometers mounted on a 1 O-meter long boom. Each interferometer collects light from two siderostats and combines them in the main optics boom (see Figure 1). Two of the three interferometers will acquire fringes on bright guide stars in order to make highly precise measurements of the spacecraft attitude. The third interferometer wi 1 I observe the science targets and measure the target positions with respect to an astrometric grid of many thousands of stars evenly distributed around the celestial sphere.

Since the science object will typically be dim (18-20 magnitude), the attitude information from the two guide interferometers will be used to point the third (science) interferometer and acquire fringes. Using this "feedforward" technique in the absence of atmospheric disturbances SIM will rapidly achieve its desired accuracy in position measurements for a single observational period.

An external metrology system is used to determine the location of each siderostat and measure the orientation and the length of the interferometer baseline vector.

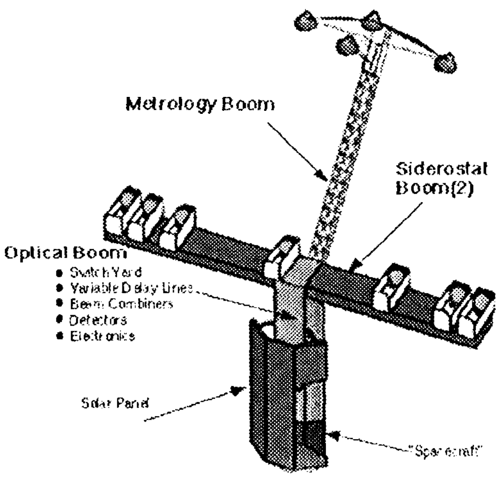

Figure 1SIM Configuration

2. Instrument Inscription

The SIM interferometer is based on an architecture derived from a series of ground based interferometers: Mark I I 1, Palomar Testbed Interferometer, and the Keck interferometer [1]. Starlight is collected by siderostats located at ends of the interferometer and redirected to a beam combiner using a series of fold mirrors. The path difference bet ween the two arms of the interferometer must be equal in order to produce a white light fringe signal. A movable delay line is used to add optical path in one arm of the interferometer and produce the white light fringe signal on the fringe detector. An internal metrology beam is used to measure the position of the white light fringe. An external laser metrology gauging system measures the three baseline vectors (the distances between the siderostat primary mirrors) from a common reference tetrahedron, and monitors minute changes in the base] ine lengths and the relative orientation between the three interferometers. This measurement, along with the fringe position information, is used to determine the angular separation between stars at the microarcsecond level.

For astrometry the quantity of interest is the angle between the star and the baseline vector and is given by the equation:

$$x = B \cos (q) + c$$

where, x is the measured fringe position, B is the baseline length, and c is an instrument offset which can be calibrated out, For synthesis imaging measurements, the fringe position gives the phase at a particular baseline length and orientation (u-v point) and a measurement of the white light fringe visibility gives the amplitude. The (u,v) plane is a coordinate system referenced to the line of sight to the target of interest. Amplitude and phase data measured at a large number of u-v points can be synthesized to form an image using techniques developed for radio interferometers.

The SIM Instrument is comprised of four primary subsystems; Starlight, Metrology, Real-Time Control and Precision Structures along with System Engineering, Modeling and Analysis and instrument Integration and Testing functions. A brief description of each of these subsystems and functions follows:

Starlight Subsystem

The starlight subsystem is comprised of the opto-mechanical hardware necessary to collect starlight and form white light fringes. This subsystem has a large number of mechanisms and high precision optics. Prototypes of these subsystems are being built and tested in a series of ground testbeds supported by the Interferometer Technology Program (ITP) (see later section in this paper).

Metrology Subsystem

The metrology subsystem provides the opto-electronic hardware necessary to measure the interferometer components to sub nanometer accuracy using a heterodyne dual frequency laser gauging system. Like the Starlight subsystem, a number of these components are currently being prototype in a series of ground testbeds being built to demonstrate measurement capability of the metrology subsystems both in ambient air and in a vacu Um.

Interferometer Real Time Computing (IRTC) Subsystem

The Real-Time Control Subsystem has the responsibility to design and deliver the Instrument Flight Electronics and real time Flight Software. Additionally, this subsystem develops the control architecture and a functioning instrument operation sequence for all modes of operation. The interferometer cent rol software is based on evolving incremental architectures originally developed for the Palomar Testbed Interferometer. Additional 1 y, a dedicated software development testbed, the Real Time Interferometer Control Systems Testbed (RICST) is also underway to develop flight quality interferometry software for SIM.

Precision Structure Subsystem

The SIM precision structure houses the hardware delivered by the three subsystems described above, The SIM structure consists of a main optics boom containing the delay lines, beam combiners, cameras, and spacecraft subsystem. Two collector booms holding the siderostat bays are deployed to give a 10 meter maximum baseline length. A metrology boom is also deployed and will hold the metrology reference tetrahedron and beam launchers for the external metrology subsystem. This subsystem is also responsible for thermal monitoring and control for the entire flight system.

Interferometer In tegration and Tes t Function

The interferometer Integration and Test function will integrate the hardware and software delivered by the subsystems described above and demonstrate that the instrument will meet its functional, performance and environmental requirements. This will be achieved through a series of incremental ground testbeds described in a later section.

Instrument System Engineering and A rchitecture Function

The System Engineering and Architecture role is described in more detail below and includes the architecture, analysis and an integrated Modeling effort that provides the algorithms needed to operate the pointing and pathlength control loops of the system

3. System Engineering and Architecture Role

A number of technical breakthroughs are required to enable the SIM mission. 'I'he function of the System Engineering and architecture task is to establish the requirements and design on the mission and instrument, interpreting the requirements and goals set forth by the Science Working Group. A summary of the driving requirements of the instrument are listed in Table 1. System engineering also has the responsibility to provide a link between the Flight Mission and a separate] y funded interferometer technology development program going on concurrently. The results of this technology development program, in the form of testbeds and models, will be applied to the analysis at the system level in order to determine whether the existing technologies and detailed designs have met the requirements of the SIM project. Over the course of the instrument development cycle, System Engineering will monitor the results of the technology development effort and correlate them into a validation and verification matrix that will be used in the integration and testing phase to prove that the system as a whole, meets or exceeds it's mission objectives.

The S1 M project has a forged a close partnering relationship with industry. Currently, three Industrial Partners are providing technical details and ideas along with developing key trade-studies, as participants of the SJM System Design Team. These studies have been analyzed and port ions incorporated into the SIM architectural trade space. As presently envisioned, the flight segment engineering functions along with the precision structure will be provided by industry.

Table 1
Requirements Summary

Instrument Requirements	
Max. Baseline Length	10 meters
# Of Baselines	3 (2 guide, 1 science)
Spectral Range	.4 -.9 microns
# Of Siderostats	7
Aperture	33 cm
Astrometric FOR	15 degrees
Instantaneous FOV	10 arcseconds
Son Avoidance Angle	50 degrees
Est. Mass	2423 kg.
Fringe Stability	10nm (r-m)
Pointing Control	15 arcseconds
Pointing Knowledge	6 arcseconds
Orbital Velocity Determination	4 mm/sec
Spacecraft Slew Rate	140 degrees in 10 min
Temperature Stability For Critical Optics	10 Mini Kelvin / hnur
Deployment Accuracy	1 mm
Science Performance	
Wide Angle Astrometric Single Accuracy	7.5 microseconds 00 18th magnitude star
Proper Motion Accuracy	3 arcseconds/yr
Image Dynamic Range	20:1
# Of (U,V) Points Per Baseline	150
Image Nulling	,0.4

Successful development of SIM requires that three grand technological challenges be met and overcome:

1) nanometer level control and stabilizat ion of optical element on a lightweight flexible structure

2) sub-nanometer level sensing of optical element relative positions over meters of separation distance

3) overall instrument complexity and the implications for interferometer integration and test and autonomous on-orbit operation.

The interferometer's complexity, with all its moving parts and control systems, is the price that most be paid for stepping beyond the paradigm of rigid monolithic telescopes as built since the days of Galileo. SIM will have to use active feedback control for at least 50 optical degrees of freedom. Another 80 degrees of freedom will need to be controlled in open loop fashion. Additional degrees of freedom will require articulation at least once for initial deployment and instrument alignment. All of this places great importance on the development of real-time software capable of autonomously operating SIM. In addition, the large data rates expected due to the complexity of the mission will challenge both the flight and ground processing capabilities. This will require an end-to-end design approach that maximizes the overall capabilities. New and creative integration and test methods will also be required to enable development of the installment at an affordable cost. The challenge for System Engineering will be to define, monitor and coordinate all these complex technologies while supporting the Project in keeping to it's schedule and tight resources.

4. Requirements Tracing

A core product of System Engineering is the development and partitioning of the functional and performance requirements. One of the ways of increasing the efficiency of the system design and architecture process is to optimize the way in which requirements are specified.

To capture all the requirements flowdown to the appropriate subsystem level, and provide a trace matrix for eventual validation of these requirements, the SIM System Engineering task has chosen to use a software requirements tracing tool called DOORS ™ from QSS, Inc. concurrently, tbe Jet Propulsion Laboratory has been developing new processes and capabilities to support missions in this endeavor. DOORS ™ has been chosen as the institutional standard, SIM will make use of this tool and a real-time team practice of levying and documenting it's requirements in a team-oriented, working environment. It is hoped that by use of an electronic method of maintaining and linking requirements at all levels, the old style of voluminous documentation can be eliminated. Further it is envisioned that unnecessary or un-allocated requirements will be found and eliminated.

This team approach to requirements development will happen in an interactive forum, utilizing what's being referred to as the '<Pit" meeting process. At the '<pit" meetings, all system and subsystem are represented. Each requirement is reviewed and allocated in real-time. In this

fashion, each party understands and accepts, rejects, or modifies the requirement on his/her subsystem. The requirements are then captured and linked between the various levels of documentation through DOORS ™. In this fashion, partial or multiple relationships can be easily viewed and analyzed in context.

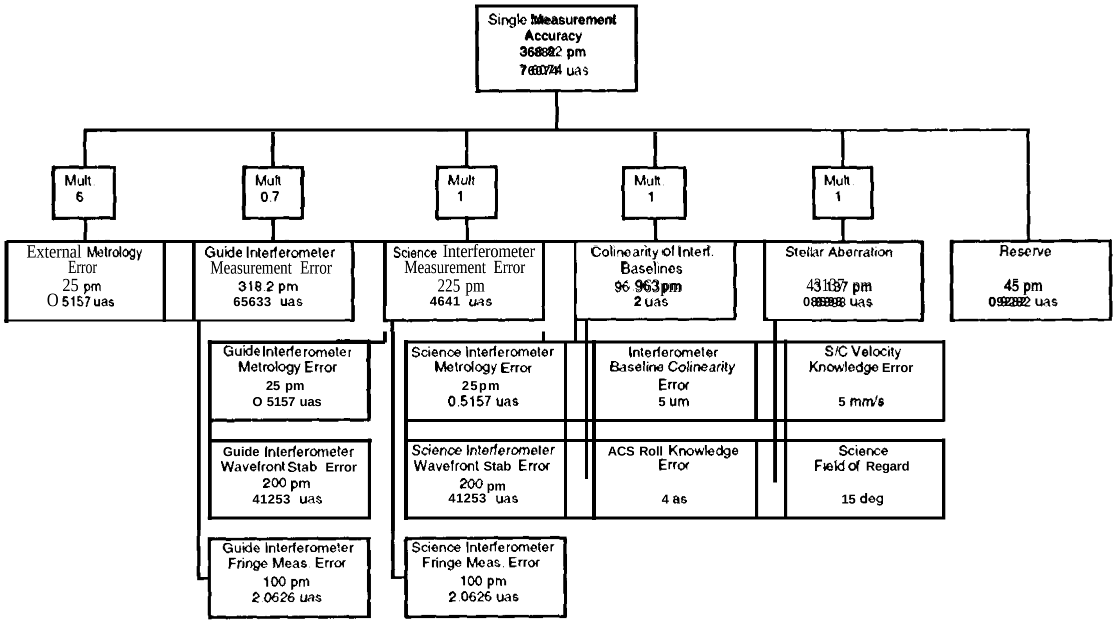

Figure 2 SIM Wide Angle Astrometric Error Budget

Due to the complexity and integral relationships of thermal, structural, optical and control systems required to meet the overall total performance object ive of 7.5 micoarcsecond single measurement accuracy, an error budget is being developed. A key approach to developing detailed requirements for the subsystems is by use of Error Budget allocations. The Error Budget method of specifying requirements conveniently fits within the DOORS™ methodology. The System Architect establishes the Error Budget. Lower level errors from different subsystems can be summed and analyzed to see if the overall Error Budget allocation has been met. Each major component of an error budget has multiplier effect on the total error. Therefore, some error sources are more impacting than others. complicating the design of SIM is the fact that the present total system level error budget for the instrument (see Figure 2) is on the order of 369 picometers (post-processing).

5. SIM Modeling

Currently with the development and allocation of the system requirements, several modeling activities are being pursued with the intent to deliver mechanisms for both establishing and verifying the levied requirements.

The complexity of space-based interferometry has been the main driver in integrated modeling for nearly a decade. The operation of the instrument is extremely intricate, involving the interaction of many subsystems that control the optical elements, the dynamic and thermal environment system, and spacecraft operations. The modeling of these interactions at both a functional or cross-cutting level and at the detailed subsystem level, necessarily encompasses several disparate disciplines and requires an integration of the models to yield a system level understanding and characterization.

Two levels of modeling are being developed that support the System Engineering task. The frost level is primarily functional in nature and is referred to as cross-cutting models. These models will be built using another JPL institutionally supported tool called Foresight™ by Nu Thena Systems, Inc. These models can be tested and modified, if necessary, prior to building and testing the flight hardware (see Figure 3). By eliminating potentially expensive re-builds and driving out system changes early in the design process, less costly development activities are envisioned.

Though reasonably simple in nature, Foresight™ allows the user to quickly build up a high-level system model of the SIM. Through a common database of systems and subsystem parameters, requirements from DOORS™ can, to some degree, be verified by these models. Using existing Functional Block diagrams as a starting point, these models will help flush out design details such as interfaces between subsystems, data bus bandwidth usage, sequence of events timelines and other system-wide issues. Timing, buffers, data system sizing and state machines can be built into, and analyzed, in these models. All areas of the SIM Design Team will be trained in the use of Foresight ™ and provide pieces of the overall system model. Use of this tool in a "groupware" fashion, will further the overall knowledge of the instrument among the team and help "flush out" open areas and identify missing interfaces. However, it will

models that are built, compared and updated based on the results of the ITP ground testbeds. These detailed models being developed for S1 M, involve the integration and capture of detailed physical processes and actions. These models address the complex interactions of optical visibility and throughput, structural deformation, modal frequencies and thermal prediction and control. As such, a simulated, detailed model of SIM, called "SIM-Sim", will be used to support system analysis and design trades as apart of the instrument definition phase of the project. Additionally, these models will be compared and contrasted to the data from the existing ground testbeds. Where necessary, the models will be updated to reflect more accurately the parameters obtained from the testbeds. Further, thermal models will be used to predict temperature excursions through the orbital period and help in the design effort to achieve millikelvin stabilities of critical optics for up to one hour.

One significant output of the detailed integrated modeling effort, is to provide algorithm development and verification for the complex control system software. These algorithms will be implemented and tested both in the detailed

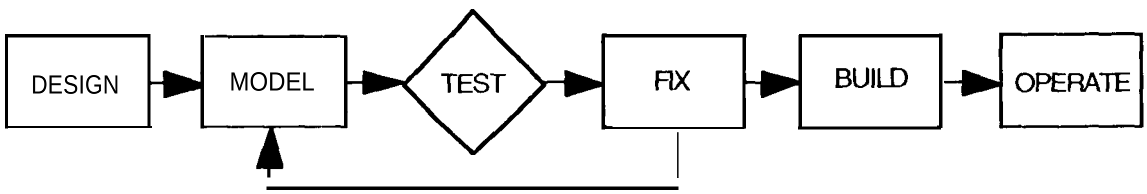

Figure 3 Model Driven Design Process

be important for the SIM team to clearly quantify the specific questions it expects the models to answer. Otherwise, without a limited set of parameters and goals, the modeling task can become an encumbering nightmare that can waste large amounts of time and defocus the team. Special care is required to constrain the modeling activities in order to maximize the anticipated output.

The second level of modeling is significantly more detailed and complex in nature. There are two types of detailed models being generated for the program. Related in nature and by use of the same tools, they differ in that the modeling activity is predicting the capability of the Flight instrument along with those that

Detailed models are necessary to support the many design and analysis activities that define

models and on the testbeds prior to being incorporated with the Flight Software.

6. Detailed SIM Models

Detailed, physics-based models of SIM will be developed and implemented that combine optical systems, structural dynamics, thermal design and control disciplines. Modeling will be done in an integrated fashion using primarily the IMOS (Integrated Modeling of Optical Systems) tool, MATLAB™, and Simulink tools. These software tools can be supplemented with traditional tools such as Code V™, NASTRAN™, and TRASYS™/SINDA™ [2].

requirements, become the basis for control design and validation, and performance prediction for these testbeds as they emulate various aspects of critical SIM functions. The models must support the design of controllers for pointing and pathlength control servos, fringe acquisition and tracking, wavefront tilt control and feed forward control. The MATLAB™ Simulink environment will be used to exercise the models, and to maintain their modularity.

Three primary models are planned in support of the SIM design and requirements evaluation. The first is the Large Angle IMOS Model. It's application is to support rotational synthesis imaging. This model is a nonlinear optics/control/structure/thermal model that is used to (1) predict OPD performance during continuous rotation synthesis imaging; (2) predict instrument response to slew torques; (3) define spacecraft slew and settling times; and (4) provide data on acquisition performance.

The second model is the Small Angle IMOS Model. It's applicability is to support astrometric predictions. This model is a linear optics/control/structure/thermal model that is used to predict OPD performance (fringe stability) during the "staring" mode of instrument operations.

The third model is the Astrometric Performance Model. This model predicts end-to-end astrometric performance; produces and analyses a simulated instrument data stream; allows the introduction of systematic errors; tests the instrument calibration process and verifies the astrometric error budget.

7. SIM Testbeds and Impacts on Modeling

A sequence of testbeds is under development to demonstrate and validate the fundamental operations and achievable performance of SIM. System Engineering will define the requirements of the testbeds, establish and evaluate the Validation and Verification Matrix and use the analysis of testbeds to support the design of the Flight article. The Validation and Verification Matrix is a system engineering method that tracks how, where and by what process requirements are proven. Some requirements are validated at a component or subsystem level. Other requirements demand system level test. Others, can only be validated by analyses.

SIM will use it's testbeds for system level testing and as a means as validating testbed models and designs. Funded by the aforementioned Interferometry Technology Program (ITP), four primary hardware testbeds will strive to prove structural stability and dynamics along with control loop processing and a fifth, software development testbed, sopports the testing of incremental capabilities of the Flight Software. These testbeds and their primary objectives are summarized below:

STB-1

An existing ITP-funded testbed, System Testbed-1 (STB-1) shown in Figure 4, was designed as a single arm interferometer and has been a testbed used to define and characterize disturbance sources, including the SIM reaction wheels. The main objectives of this testbed are to demonstrate that a positional stability requirement of less than 10 nanometers can be achieved in ambient air disturbance environment and predict that this requirement is achievable on-orbit. Demonstrating these requirements on this testbed is difficult as the testbed, like the Flight instrument itself, consists of many optical and mechanical components distributed across a 10 meter long flexible structure. As a part of the laboratory testing, this testbed is excited by mechanical disturbances, namely attitude control system reaction wheels, in order to characterize their effects on interferometer stability and control systems design. Results to date have shown that ST B- 1 has proven that 8 nanometer (run)

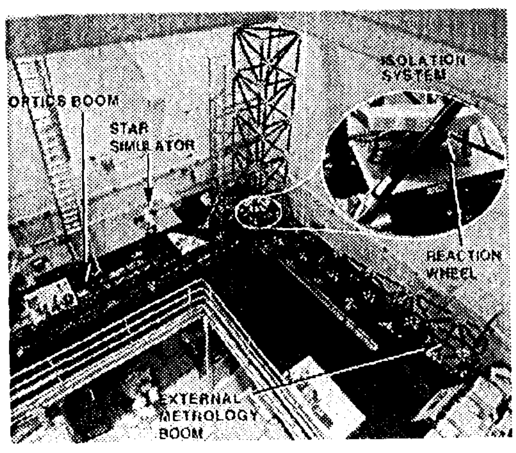

Figure 4 A View of the STB-1 Testbed

stability is possible in ambient air (see Figure 5), meeting it's performance requirements. Further, this testbed has been used to validate many of the integrated modeling tools that will be used in the design performance predictions of the flight SIM.

STB-2

A follow-on to the STB- 1 article is the System Testbed-2 (STB-2). This testbed will add a second interferometer. It's primary requirement is to demonstrate that a feed forward method to pass pointing information from the guide interferometers to the science interferometer baseline is possible allowing SIM to observe dim stars. By adding a second baseline, integrating SIM-like "flight" software from RICST, and exploring further ground and flight environment isolation (both active and passive), this testbed will support the incremental validation of the SIM system requirements through testing.

MAM

The Micro-arcsecond Metrology (MAM) testbed is a testbed that will demonstrate micro-arcsecond astrometric measurements of an artificial star that can not otherwise be done in ambient air. The MAM will include the interferometer, the metrology gauging system and the artificial star in a vibration isolated, thermally stable vacuum tank. MAM is designed to achieve the same precision in white-light fringe detection and metrology gauge performance as S1 M.

RICST

The Real-Time Interferometer Control System Testbed (RICST) is a embedded real-time software testbed. A closed loop test environment is developed in the RICST facility that includes breadboard hardware components along with the software components. This testbed provides the facility and the environment for the testing of incremental deliveries and versions of software for an integrated interferometry program. The software under development will support multiple programs including both ground and flight interferometers. By using a core set of software code modules, incremental approaches to delivering SIM Flight Software should benefit the Project.

STB-3

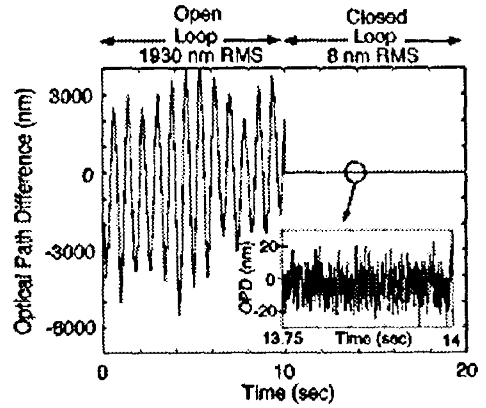

Figure 5 STB-1 8nm Closed Loop Results

The key testbed in the technological development effort for SIM is the System Testbed-3 (STB-3). STB-3 will be a three baseline interferometer that is functionally equivalent to, and with all the inherent complexity of, the SIM Flight article (see Figure 6). S1 M instrument System Engineering will develop the high level requirements with which the STB-3 testbed article will designed. The SIM Testbed-3 design will be as similar to the current SIM instrument design as practical within the cost constraints. SIM Systems Engineering will calibrate and apply the test results of STB-3, and other ground testbeds, to the expected on-orbit performance of the SIM via the integrated modeling efforts. A separate STB-3 requirements document will be developed concurrently with the SIM Instrument Requirements document. The component fidelity of STB-3 will be driven by a combination of cost and realizable ground performance.

The system engineering approach to the STB-3 development activities will attempt to resolve these limitations, consistent with the design and integration approach being taken in developing the SIM instrument. As a result, STB-3 will be the pathfinder for many of the design trades and integration activities that would normally be associated with the flight instrument development. The STB-3 will provide an opportunity to integrate incremental deliveries of control systems software, simulated spacecraft engineering functions and high precision laser gauging technologies. System Engineering will also develop and track the test objectives and performance metrics and report on the STB-3 Validation and Verification Matrix.

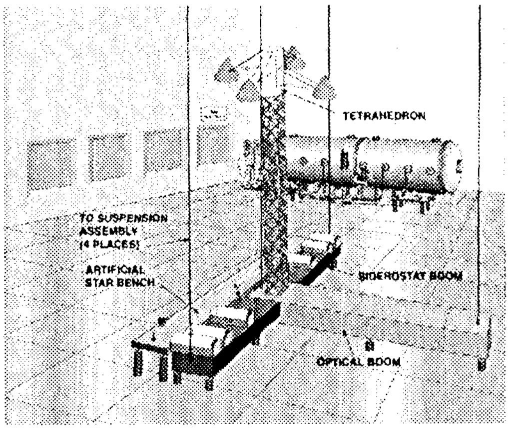

Figure 6 STB-3 and MAM Testbeds

This testbed is envisioned to provide the full functionality of flight instrument and system along with a testbed article that system-level Verification and Validation can be accomplished. Key functional and performance requirements of this article are to prove that nanometer-level pathl ength stabilization is possible in ambient air. Specifically, STB-3 will establish the technology readiness to implement SIM Flight hardware vibration attenuation systems that provide: 1 nanometer Optical Path Difference (OPD) stability over one second integration time of a single baseline and 10 nanometer OPD stability over one millisecond integration time of all three baselines [3]. The first requirement is derived from a starlight nulling requirement while the second requirement is derived fro the need to maintain adequate fringe visibility of both the guide star and the science star interferometers during astrometry and imaging operations.

STB-3 will also establish the technology readiness to implement in flight software and autonomous real-time interferometer cent ml system capable of operating SI M within the operational and control system constraints of the electronics systems [4]. Other objectives of this testbed are to develop and document the integration and performance validation approach for the SIM instrument, exclusive of launch dynamics and on-orbit thermal conditions. STB-3 will also demonstrate closed and open loop control and data analysis and reduction software in all modes of instrument operation. Additionally, an end-to-end checkout of the entire system, remote alignment of the optical elements, exercise of full complexity of SIM and verification of the system are planned. The validation of system level requirements for accuracy, visibility and throughput are a key driver for this testbed.

Systems Engineering will lead the development of the requirements for the SIM design concept from which the STB-3 will be derived. SIM Systems Engineering will calibrate and apply the test results of STB-3, and other ground testbeds, to the expected on-orbit performance of the SIM via the integrated modeling efforts. Finally, lessons learned from the development and testing of the STB-3 will be applicable to the system design of the SIM flight article.

Additional goals for the testbed are to train the people, establish the procedures for integration and find out problems early in the SIM development cycle. The experiences gained by building a fully functional ground version of the instrument to the highest common fidelity possible will benefit SIM greatly.

By following flight like approaches to systems engineering, integration and test, the experiences can be captured in both documentation and knowledge in such a way as to be directly applicable to SIM, retiring risk earlier in the design process.

Testbed Modeling

The System Engineering effort will also encompass a modeling activity that develops integrated models of the ITP ground testbeds (MAM, STB-1, STB-2, and STB-3) for subsequent use in control design, simulation, performance prediction and a posteriori data analysis. As each testbed demonstrates one or more critical SIM functions or capabilities, the process of developing these models will also serve to illuminate the counterpart model development tasks concurrently underway for SIM. These models will be contrasted with actual results extracted from the testbeds. The models will be updated and modified, as necessary, based on the testbed results.

The Integrated models of the testbeds wi II include the design of control loops, diagnosis of problems during testbed build and operation, and ultimately the validate the testbeds, i.e. is the process well enough understood so that the achieved performance corresponds to predicted performance? Many elements of this modeling process have already been STB-1 with the integration of the structural and optical models via the IMOS tool. Excellent fidelity has been established between predicted and measured rtns OPD error using this approach. The integrated modeling task on STB-3 will be more challenging than for the STB-1 because of greater functionality and additional baselines. However, by maintaining a high level of fidelity between the models and STB-3, use of the models and their development methods will ultimately support the systems analysis necessary for accurate predictions of SIM's actual on-orbit performance.

8. Conclusion

As discussed in this paper, SIM System Engineering is embracing new institutionally supported methods of requirements development, modeling and testing. Using a suite of software tools andhardware testbeds early in the design phase of the mission, it is envisioned that the penetration of the design details will be traceable, modeled and tested in an integrated way to validate that the SIM mission will meet it's on-orbit performance requirements in an effort to reduce or mitigate risk earlier in the design phase of the mission. A key factor in taking this new approach is to optimize the design process, produce testbeds and models early in the design phase and find innovative ways of meeting the overall Project objectives and constraints.

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